Nasmyth Calibration Unit **wht-naomi-42**

This document is an update of the NCU section in the OMC PDR documentation to reflect the updated requirements (AOW/SUB/RAH/5./06/08/98) and changes to the implementation since the PDR.

Section 1 gives a summary of and comments on the requirements in the OMC WP.
of the OMC
Section 2 gives the functional requirements and specifications for the components in the NCU
The NCU is positioned between the WHT Nasmyth de-rotator and the Nasmyth focal plane. It provides

i) a variety of small aperture sources of illumination over a spectral range of 0.5 to 2.5 ?m and is expected to be used extensively during laboratory testing of the OMC and during integration with the WFS. At the telescope it will be used to confirm the laboratory tests and, during observations, for regular checks on the alignment.

ii) A 40 x 40 arcsec flat field source with a wavelength range of 0.5 – 2.5 ?m

iii) an f/11 laser beam which is used for alignment of the NCU to the imaging/correcting optics. This laser beam will also be used in the alignment of the OMC to WFS and for visual checks of the system in the case of any malfunction.

1. NAOMI calibration

The calibration requirements for NAOMI are given in Section 1.1 below. Functional requirements for the NCU were derived from these and are detailed in Section 6.2 of the OMC WP document. A commented list of requirements from Section 6.2.1 of the OMC WP document is given below in Sections 1.2.1 to 1.2.13. The items have been reordered to reflect their grouping in the implementation of the NCU; the original requirement number is shown in square brackets.

1.1 Calibration requirements

1. Mapping of distortion – Nasmyth focal plane to WFS probe space	In order to perform astrometric observations using NAOMI the distortions from sky to science camera and WFS probe space need to be known. The focal plane can be sampled using astrometric standards but interpolation of these data will be required using internal reference sources.
2. Mapping of aberrations (Zernike>tip-tilt) – Nasmyth focal plane to science ports and WFS	There will differential aberrations between an off-axis guide star and an on-axis science object. Part of the setting up procedure before an observation will be to introduce offsets into the WFS/DM control loop to allow for these differences. By mapping the aberrations across the fov the procedure for optimising an IR on-axis image (or a visible image at the optical science port) and obtaining the corresponding WFS offsets will be considerably shortened.
3. Mapping of IR detector, IFU and/or slit onto WFS probe space	The position of the science detector/entrance aperture need to be known in WFS probe space so that an object with a guide star at a known offset can be centred on the detector/entrance aperture.

4. WFS transfer function	The WFS will operate with non zero offsets. The transfer functions for each of the sub-apertures needs to be measured using a source which gives diffraction limited images and using a ‘turbulence broadened’ source.
5. Response of NAOMI to a moving source.	For commissioning and test purposes the NCU should provide a source which can be moved using either a regular (sinusoidal) waveform or a tip-tilt waveform measured previously using the NAOMI or other WFS.
6. Modal decomposition of the WFS signals	The modal decomposition algorithms of the control software and the performance of the DM when they are re-applied as corrections must be tested. This can be done by introducing calibrated static optical aberrations.
7. Pupil simulator/DM illumination	The NCU should provide two f/#’s f/11 to simulate illumination of NAOMI by the WHT f/8 so that the full 76 mm aperture of the ELECRA DM is illuminated A mask should also be provided that simulates illumination of NAOMI by the telescope including central obscuration and vanes, at least for an on-axis source. One use of this mask will be to measure the WFS transfer functions for partially illuminated sub-apertures.
8. Visual inspection of the optical alignment of the OMC and WFS separately and to each other	Experience with other instruments shows that it is very useful to have a bright laser source available for initial alignment and visual checking of the system. If possible both an f/11 and a ‘pencil’ beam should be implemented This light source will also be used to align the NCU to the OMC.
9. Pre-correction stellar/ calibration source position. Guide star acquisition	A pre-correction camera is required as an acquisition camera for NAOMI. The option to view a star at the same time as the calibration source is required to confirm mutual alignment of calibration unit and telescope. In addition the camera will be used to measure the pre-corected image of a star of calibration object in order to evaluate the gain being made by the AO system.

10. Flatfielding of science instruments and the WFS	The WFS is flatfielded by focusing the WFS CCD on the clear aperture in the lenslet wheel. This requirement is provided by the f/11 and f/8 illumination of the DM. Science instruments **Imager**. The fov of an imager with a 1024 x 1024 detector and 0.04 arcsec/pixel is 41 x 41 arcsec. This corresponds to 9.2 x 9.2 mm at the Nasmyth focal plane. **Long slit spectrometer**. A spectrometer will require a broadband, spectrally smooth, flat fielding source. It is unlikely that the slit length will be > fov of the above imager. **IFU**. The fov of an IFU used with NAOMI will be << fov of an imager and therefore the imager FF source will be large enough. Requirements for the uniformity, flux levels and wavelength range for these FF sources are given in section 6.2.2 of the OMC WP
11. Narrowband Spectroscopic calibration	Provision should be made to illuminate a laser WFS with a Na 589nm source within the NCU Provision should be made to have other (how many??) spectral lamps feeding the NCU for spectral calibration of the spectrometers being used with NAOMI

1.2 Derived NCU requirements

Note. Numbers in [ ] refer to the number of the NCU requirement in Section 6.2.1 of the OMC WP.

The requirements in sections 1.1.2.1 to 1.1.2.13 are those listed in section 6.2.1 of the OMC WP; further details of these requirements are set out in sections 6.2.2 to 6.2.7 of that document. What is given here are derived parameters such as pinhole size and positions and some implementation details. Positional accuracy is specified in the WP document.

1.2.1 A diffraction-limited (at K band) point source close (2-3 arcsec) to the axis for calibration of the WFS offsets for best IR image. [4]

Calibration requirements 2, 3 and 4

The diameter of the pinhole for this source

= 1.22 ? f/#(WHT)

= 1.22 . 2.2 . 10.94

= 29 ?m

= 0.13 arcsec

There are several sources to be used near the on-axis position - this one is on the axis.

1.2.2 An array of off-axis sources for mapping the AO optical system distortion and wavefront aberrations over the field of view [10]

Calibration requirements 1, 2

These sources will have a diameter of 44.6 ?m (?0.2 arcsec) so that the sub-aperture images at the WFS are diffraction limited. They will be on a square grid with separations of 6.5 mm (?29 arcsec) giving 7 images across the Nasmyth fov of 1.45 arcmin.

This array of sources is used primarily for measuring distortions and aberrations of the NAOMI optics and so that relative flux levels from source to source can vary over the dynamic range of the WFS CCD. This should be at least a factor of 2. Don't understand this last bit about varying flux levels ??

1.2.3 An on-axis diffraction-limited (in visible region over full aperture) point source [1]

Calibration requirement 2

The diameter of the pinhole for this source

= 1.22 ? f/#(WHT)

= 1.22 . 0.7 . 10.94

= 9.3 ?m

= 0.04 arcsec

There are several sources to be used near the on-axis position - this one is placed at x=-10 arcsec.

1.2.4 An on-axis non-diffraction-limited source (approximately 1 arcsecond) [3]

Calibration requirement 4

The diameter of the pinhole for this source = 223 ?m

There are several sources to be used near the on-axis position - this one is placed at y=-10 arcsec.

All the sources in items 2.2.1 to 2.2.4 are implemented using a focal plane mask illuminated by light from the NCU over the spectral range 0.5 to 2.2 ?m.

1.2.5 Neutral density and spectral filters for controlling the intensity and colour of all broad band sources listed above [13]

Calibration requirements 1 to 6

To meet the flux requirements in both the IR science camera and the WFS it will be necessary to change the shape and magnitude of the blackbody spectrum which enters the system. Also the WFS transfer function needs to be calibrated using a source with various effective colour temperatures to simulate guide stars of differing spectral type. Flux requirements are specified in Table 2 in Section 6.2.2 of the OMC WP, reproduced below as Table 1.

Spectral Band (µm)	Radiant Intensity (W ster^{-1})
0.5 to 1.0	1.6 x 10^{-8}
1.0 to 1.5	4.0 x 10^{-9}
1.5 to 2.0	9.0 x 10^{-10}
2.0 to 2.5	2.5 x 10^{-10}

Table 1

1.2.5.1 Implementation

A spreadsheet has been developed which takes into account the transmission of all the elements of the NCU including the efficiency of the integrating sphere and uses a blackbody spectrum for the temperature of the tungsten halogen lamp to calculate the radiant intensity at NFPM. Table 2 gives the required radiant intensities from the OMC WP together with those calculated from the spreadsheet.

The values in the table below were calculated using a 10 W tungsten halogen lamp with a colour temperature of 2800 K. It was assumed that 50% of the power is converted to BB

radiation. The ISM pinholes are 1 mm diameter, the NFPM pinholes are 44.6 ?m diameter and the reflectivity of the beamsplitter is 30%.
The expected radiant intensities meet the OMC WPD requirements as shown in Table 2. When the modelled intensities are converted to detected photons at the WFS and IR detectors taking into account transmissions of all components from source to detector, it can be seen from columns 3 and 4 of Table 3 that there is more than sufficient flux even at an integration time for the WFS of 5 msec.
The light source used and real transmissions, reflectivities and detector QE's may change these detected photon rates by a factor of 2 up or down. The amount of attenuation needed will be determined during laboratory commissioning.

Spectral Band ?m	Radiant Intensity at NFPM (W ster^{-1})	
	Requirement from Table 1 above	Modelled
0.5 to 1.0	1.6 x 10^{-8}	1.69 x 10^{-8}
1.0 to 1.5	4.0 x 10^{-9}	4.08 x 10^{-9}
1.5 to 2.0	9 x 10^{-10}	9.78 x 10^{-10}
2.0 to 2.5	2.5 x 10^{-9}	2.63 x 10^{-10}

Table 2

?? The numbers below must be over-specified, at least for the IR. It is unlikely that the IR detector can cope with >> 10^5 e^- per frame.

??	Photons /subap/5msec at WFS from 0.2" calib source for Mode 1	Photons/sec at IR detector from 0.2" calib source	Photons/sec at IR detector from 0.13" calib source	Photons/sec/0.04" pixel at IR detector from flat field source
0.5-1?m	1.02E+06			
J		1.36E+11	5.73E+10	6.90E+09
H		1.02E+11	4.29E+10	5.18E+09
K		4.90E+10	2.07E+10	2.50E+09

Table 3

1.2.6 A fast low-amplitude tip/tilt motion of the above source [2]

Calibration requirement 5

The sources referred to here are 0.2 arcsec diameter for the WFS signal and 0.13 arcsec for the IR image. The focal plane mask used for the static calibrations cannot be used for these sources, they are implemented by on-axis pinholes at the NCU input. The tip-tilt motion is generated in the NCU by a piezo mounted mirror.

1.2.7 An on-axis f/11 laser beam for initial alignment [6]

Calibration requirement 8

This beam is used for alignment of the NCU to the main imaging optics. It follows the same path as the white light within the NCU.

1.2.8 A laser pencil beam if readily implemented [7]

Calibration requirement 8

1.2.9 A WHT pupil simulator using a mask [8]

Calibration requirement 4

The NCU will provide either a f/11 or f/8 beam, without central obscuration, for the various point and extended sources using either

i) For f/11 a mask placed just in front of the secondary mirror of the Offner relay or

ii) For f/8 the physical size of the secondary mirror.

The pupil simulator mask including a central obscuration and vanes does not have to be placed at a pupil image if it is used only with an on-axis image. For example it can be placed in the collimated beam between the DM and OAP2. An advantage of placing here is that it is 56 mm in diameter and the width of the vanes can be accurately simulated.

1.2.10 A feed for a pre-correction camera [9]

Calibration requirement 9

So that the NCU can feed light to both the OMC and the pre-correction camera a 50/50 beamsplitter is inserted in front of the Nasmyth focus. This implementation also allows the pre-correction camera to see the NCU images and sky image simultaneously.

The preferred camera as detailed in section 6.2.4 of the OMC WP is the Cohu 6400. This has a image area of 8.8 x 6.6 mm (?39 x 26 arcsec), the pixel size is 11.7 x 18 ?m (?0.05 x 0.08 arcsec). A small wedge angle (2^o) on the beamsplitter substrate moves ghost images by 12 arsec i.e outside the the fov of the WFS and far enough away from the main image to be clearly identified in imaging detectors.

Using a QE curve on a Cohu6400 the detected photon rate for V=16 stars of different spectral type have been calculated and are given in Table 4. what about camera/video noise - this can render a million photons undetectable??

O9	B0	A0	F0	G0	K0	M0	M5
16823	16876	12793	16203	18133	20897	45141	113837

Table 4 Pre-correction detected photons/sec for V=16 star

1.2.11 A means of generating known static aberrations [11]

Calibration requirement 6

As with the pupil simulator it is easier to implement this external to the NCU. It will be implemented as a pair of tilted lenses or a non-flat piece of glass either of which will have been calibrated with an interferometer. A common mount will be used for the pupil simulator and this aberration generator.

1.2.12 A turbulence generator for use during laboratory tests [12]

A design for this has not been developed but as this is for laboratory use the turbulence generator can be positioned where the derotator would normally be and a turbulence broadened image placed directly at the NAOMI input focal plane.

1.2.13 A 40-arcsecond diameter flat-field source for IR and optical science instrument calibration [5]

Implemented as a 10mm square aperture in the NCU input mask.

Flux requirements are given in Table 3, section 6.2.2 of the OMC WP reproduced below, Table 5.

Spectral Band (µm)	Radiance (W $ster^{-1}$ cm^{-2})
0.5 to 1.0	1.6 x 10^{-3}
1.0 to 1.5	5.8 x 10^{-4}
1.5 to 2.0	1.6 x 10^{-4}
2.0 to 2.5	1.9 x 10^{-4}

Table 5

Using the model described in section 1.2.5 the total detected photon rate per 0.04 arcsec pixel is as shown in the last column of Table 3. If the calibration unit is used to flat field an IR imager then, as is shown below, the total number of photons which need to be detected per pixel is ~ 10^8. Therefore the fluxes will be more than adequate but due to uncertainties in the light source such as the proportion of electrical power converted to BB radiation and the wavelength dependance of both the emissivity of the filament and transmission of the envelope the actual signals and amount of attentuation will need to be determined during commissioning.

1.2.14 Uniformity of the flat-field source.

1.2.14.1 Requirement

When making IR observations the background signal has to be subtracted from the raw image to obtain images which contain only astronomical sources. The astronomical sources can be orders of magnitude fainter than the background levels need to be very accurately determined. Background levels can be measured by

a) using a blank area of sky near the astronomical source
b) taking a series of overlapping images such that at least one contains blank sky
c) taking an image of a nearby blank field after the science image. This image needs to be taken quickly enough for the sky level not to have changed between images - usually <1minute.

Method a) is most likely to be used for images obtained with NAOMI and requires that over scales of ~ 1-2 arcsec the relative sensitivities of the pixels is known to an accuracy of <0.5%. For example if NAOMI is used to observe a K=21 mag object for 400 sec the detection is 5? If the flat fielding errors are 0.1% RMS. This is reduced to 4? if the flat-fielding errors are 0.5% RMS as specified in the OMC WP.

The overall variation in the flat-field source can be less stringent than the small scale uniformity and if necessary can be calibrated using a sky flat. A large scale variation will appear as an error in relative photometry across the field and if the variation is kept below 2% it will be below other sources of error.

1.2.14.2 Implementation

The radiation at each point in the fov of the flat-field source comes from an area about 9mm in diameter on the inside of the integrating sphere so that the overlap between points a few arcsec apart will be >90%. The Labsphere catalogue gives no values for the uniformity of Spectralon, the material to be used in the NCU integrating sphere, but because the scattering occurs in the the 7mm thickness of the material and not at the surface the uniformity of the radiance of the sphere wall will be <<1%. Additional smoothing of the flat-field image as seen by the science instruments could be achieved by moving the FSM during flat-field integrations.

The centre to edge variation in the intensity of the flat -field source depends on the geometry of the output (see Figure 1) and in particular on the ratio of the diameter (d) of the area to be illuminated over the diameter (D) of the exit port and the ratio of the distance (x) from exit port to illuminated surface over D. The ratio of edge to centre intensities as a function of x/D and d/D is shown in

Figure 2. This plot shows that to keep centre to edge variation below 5% the exit port should be bigger than illuminated area and that the illuminated area, in this case a plane conjugate to the Nasmyth focal plane, should be as close as possible to the exit port. The diameter required for the flat-field source is d=10mm. If we make D=15mm (d/D=0.67) and x=1mm (x/D=0.067) then $E_e/E_0 \tilde{}$ 0.95.

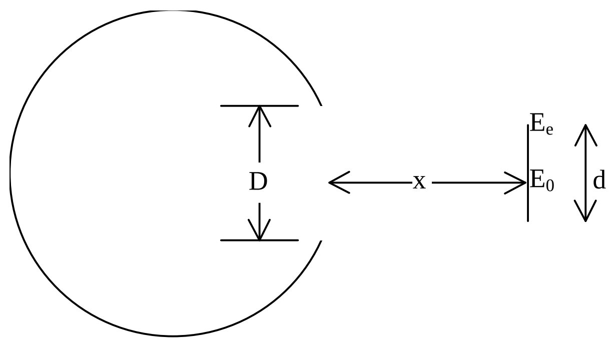
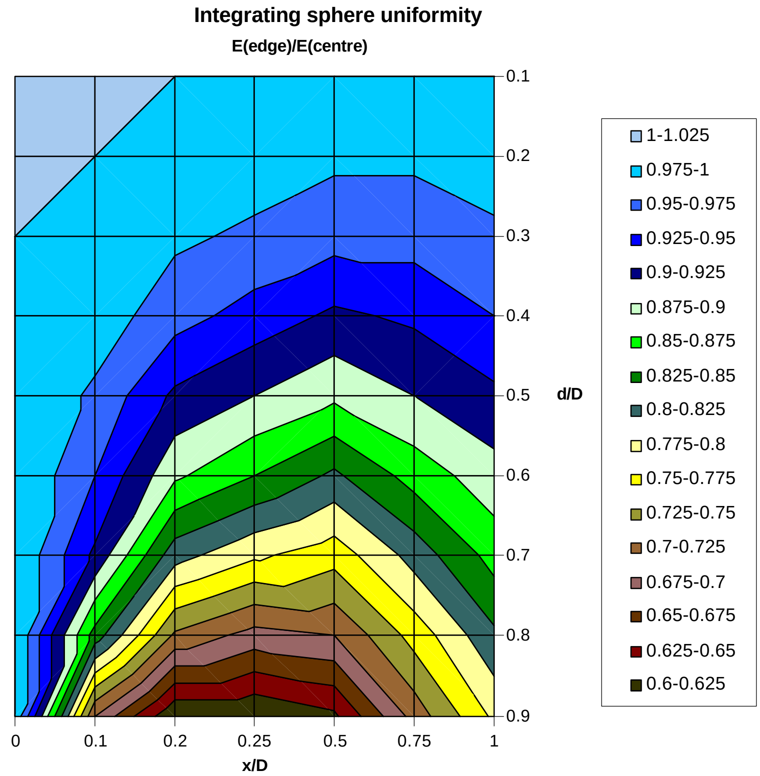


Figure 1

Figure 2



Integrating sphere uniformity
E(edge)/E(centre)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
d/D
0
0.1
0.2
0.25
0.5
0.75
1
x/D
1-1.025
0.975-1
0.95-0.975
0.925-0.95
0.9-0.925
0.875-0.9
0.85-0.875
0.825-0.85
0.8-0.825
0.775-0.8
0.75-0.775
0.725-0.75
0.7-0.725
0.675-0.7
0.65-0.675
0.625-0.65
0.6-0.625

2. Component functional requirements and specifications

Component	Purpose/requirements	Specification
Laser	Provides radiation for alignment Adjustment ranges Linear Don't understand why tilt adjustments aren't needed ?? Tilt Adjustment step size	Power x, y z x-axis y-axis z-axis x and y offsets
White light source	Provides 0.5-2.5 ?m radiation for distortion/aberration measurements	
Attenuator	a) Fixed. To adjust overal signal levels b) Variable. To adjust light levels of calibration radiation	ND Attenuation
Colour correction filters	To convert white light source colour temperature to that of stars of various spectral types	Mired ?? shift for N temperature i.e. from31 $=10^6(1/T_{K0} - 1/T_{lamp})$
IS mask	To provide a flat-field source science instruments To provide illumination for pinholes in Nasmyth focal plane mask	Aperture size Hole positions Hole size Additional pinholes
Offner Relay 1	Together with Relay 2 provides 1:1 imaging of the IS mask onto the Nasmyth focal plane mask	Radius of curvature Clear aperture
Offner Relay 2	Together with Relay 1 provides 1:1 imaging of the IS mask onto the Nasmyth focal plane mask Acts as fast tip-tilt injection component for the NCU	Radius of curvature Clear aperture
Relay 2 mount	Tilts Relay 2 about 2 axes Tip-tilt range Frequency range	 x, y-axes
Beamsplitter	Reflects part of light from NCU towards the Nasmyth focus Transmits part of light from NCUto pre-correction camera Reflects part of light from sky to pre-correction camera Transmits part of light from sky towards the Nasmyth focus	
Pre-correction camera	Used to acquire astronomical targets, observe stellar images before correction by the AO system and to measure the position of the NCU point sources	